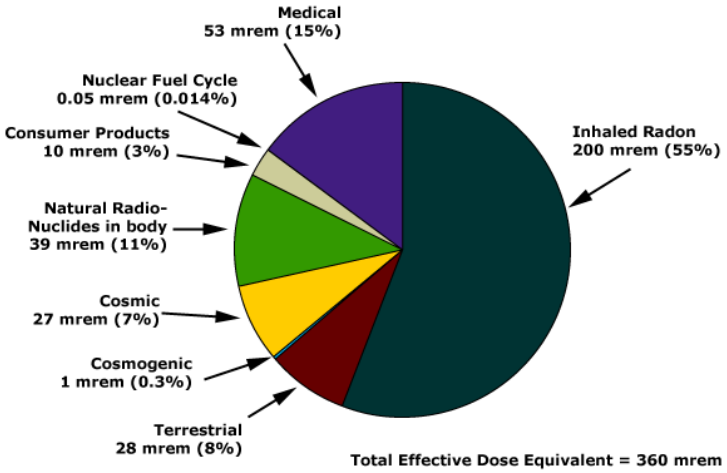
Radiation Basics

Our Radiation Environment

We live in a radioactive world where we are all exposed to ionizing radiation every day of our lives. It is called natural background radiation and varies around the world. Sources of background radiation are illustrated in the pie chart below.



This chart shows that the average American receives a total equivalent dose of around 360 millirem (mrem) per year. A millirem is a very small unit of measure. To better understand the relative insignificance to human health from a millirem of radiation, the average dose from watching color TV for a year is 2 mrem. Passengers on a roundtrip transatlantic flight receive a radiation dose of about 5 mrem just due to the plane's altitude above the Earth, which exposes them to more cosmic radiation. Employees of New York's Grand Central Station are exposed to about 120 mrem each year from the uranium and thorium in the granite used in the building's construction. Radiation exposure for residents of Denver, Colorado is about 50 mrem more each year than residents of Los Angeles, California because of Denver's greater altitude.

Depending on one's location in the world, the individual contributors to background radiation dose may vary somewhat in percent, and more so in quantity, from the representative numbers shown in the pie chart.

Terrestrial radiation is from radioactive material in the ground beneath us. This material is primarily the product of uranium and thorium radioactive decay. Both of these elements are plentiful in the Earth's crust and because they have been decaying since the Earth's formation, there has been a

substantial buildup of the radioactive **isotopes** produced in their decay chains.

Cosmic radiation comes from our sun and other radiating objects in the universe, such as supernovas that produce extremely high energy, heavy, charged particles. Cosmogenic radiation is radiation resulting from cosmic ray interactions with atoms in Earth's atmosphere.

Radioactive material contained in the human body is dominated by potassium-40 and carbon-14, radioactive **isotopes** of potassium and carbon, respectively.

Radiation is received from consumer products such as color television sets, clocks and watches, and various building materials such as cement, concrete, and gypsum, which contain uranium and thorium.

Medical radiation consists primarily of diagnostic x- and gamma-rays.

It is quite evident from the pie chart above that the largest single contributor to total background radiation dose is radon. Radon is a gas produced in the uranium and thorium radioactive decay chains (the primary sources of terrestrial radiation). Because it is a gas, radon migrates up through the soil and becomes part of the air we breathe. Despite claims made by various organizations, radon is <u>not</u> the leading cause of lung cancer in non-smokers.

Some of what we eat is also radioactive, with potassium-40 being the primary contributor because potassium is so pervasive in our environment. Examples of foods containing potassium-40 include Brazil nuts (which also contain radioactive radium-226), lima beans, bananas, white potatoes, carrots, and red meat.

We need to remember what Paracelsus once said: The dose makes the poison. This is also true of ionizing radiation. While high doses can cause cancer, low doses are not health hazards, as evidenced by chronic exposure to natural background radiation.

Radiation Risk

Alpha radiation has a very high linear energy transfer (LET) and therefore relatively low penetrating power. In fact, alpha radiation has a range in air of only one and one-half inches. That is, interactions with air molecules causes alpha radiation to lose all of its energy in about one and one-half inches of travel from the source. Alpha radiation can be effectively blocked by card stock material and cannot penetrate the dead layer of human skin.

Although beta radiation has a much larger range in air and therefore more penetrating power than alpha radiation, it can be blocked by a sturdy sheet of plexiglass. With the exception of very high energy radiation, beta radiation also cannot penetrate the dead layer of human skin.

Both gamma-rays and x-rays can penetrate the human body, which is why they are used to image internal body organs.

So, although external exposures to alpha and beta radiation are not hazardous to health, exposure to gamma-rays and x-rays may present a health hazard, particularly if the energy is very high and the exposure time is long.

The α β γ's of Radiation

Ionizing radiation has sufficient energy to dislodge orbital electrons when interacting with atoms, thereby creating positively charged ions. Hence the name, ionizing radiation.

The forms of ionizing radiation to which humans are commonly exposed are called **alpha**, **beta**, **x-ray**, and **gamma-ray**. The first two forms, alpha and beta, are subatomic particles that have mass. Alpha radiation is a helium nucleus (two protons and two neutrons), and beta radiation is an electron. Both originate from radioactive decay of matter.

X-ray and gamma radiation are electromagnetic waves that have no mass. Like alpha and beta radiation, gamma rays originate from the radioactive decay of matter, while x-ray radiation is generated in x-ray tubes.

Measuring the Invisible

We quantify radiation exposure using metrics that characterize the energy deposited from radiation interactions with matter. The metrics associated with such interactions are called **linear energy transfer** (LET) and the **radiation absorbed dose** (rad). LET is the energy deposited by ionizing radiation per unit distance of travel through matter, and absorbed dose is the energy deposited in matter per unit mass of material. The biological effects of radiation depend on both its LET and the absorbed dose.

Alpha particles, being massive compared to beta particles, have a very high LET in matter and therefore relatively low penetrating power. Beta particles and gamma-rays have very low LET in matter and therefore much higher penetrating power than alpha particles.

Absorbed doses of radiation are measured in units called rads or Grays. The difference is that the rad is the traditional unit for radiation absorbed dose, and the *Gray* (Gy) is the International System unit. One Gy is equivalent to 100 rad. While these units apply to any radiations and materials, they are used primarily with biological systems.

Biological Effects

For biological systems, it has been convenient to define a *relative biological effectiveness* (RBE) for the various types of radiation. This accounts for the different effects that each type of radiation — alpha, beta, x-ray or gamma — exerts on an organism.

RBE also depends on the dose, the dose rate, and other factors. The upper limit of RBEs for a specific type of radiation is called the *quality factor* (QF).

In 1977, the International Commission on Radiological Protection (ICRP) recommended using quality factors of one (1) for x-rays, gamma-rays, and beta particles, and 20 for alpha particles.

We can multiply the quality factor by either rads or Grays to come up with a much more useful metric called **equivalent dose**. Why is it more useful? The equivalent dose accounts for the biological effect of ionizing radiation, no matter whether its form is alpha, beta, x-ray, or gamma.

If we only referred to radiation in terms of rads or Grays, we would always have to specify the type involved. Instead, equivalent doses account for each quality factor, and can therefore easily be added together to describe the cumulative effect of all radiation exposure. Equivalent doses of radiation are expressed in units called rems or Sieverts.

A rem is the traditional unit of equivalent dose. It is equal to the dose in *rad* multiplied by the *quality factor* for the radiation type. For low LET radiation (beta, x-rays and gamma-rays), one rad is equal to one rem.

Of course, there is also an International System equivalent dose: a unit called the *Sievert* (Sv). The dose in *Sievert* is equal to the dose in *Gray* multiplied by the radiation type quality factor. Similar to the traditional system of measurement, for low LET radiation (beta, x-rays and gamma-rays), one Sievert is equal to one Gray.

There is also a very convenient conversion factor between traditional and International System units: 100 rems equal one (1) Sievert.

Latest Research

More recently, the use of *quality factors* has come under some criticism for not accurately characterizing actual biological effects. *Tissue weighting factors* have been proposed as being more appropriate to use for calculating dose, so that dose is then dependent on the specific biological tissue receiving the exposure. (Some tissues are more susceptible to radiation damage than others.)

In 2007, the ICRP recommended that *equivalent dose* in a tissue or organ be weighted to represent the relative contribution of that tissue or organ to the total biological effect resulting from uniform irradiation of the body, where the sum of tissue weighting factors is equal to one.

Acute vs Chronic Dose

A dose accumulated over a very short period of time is said to be an *acute* dose, while one accumulated over an extended period of time is

said to be a *chronic dose* (e.g., natural background radiation from things such as soil, food, water, and air). Though the word “chronic” makes it seem bad, natural background radiation is not only harmless, but also necessary to maintain optimal health.

Even if a cumulative chronic low dose is equivalent to a dangerously high acute dose, since it accumulates over time, it is not as harmful. The body’s adaptive protection systems are effective in repairing radiation-induced damage from chronic low doses.

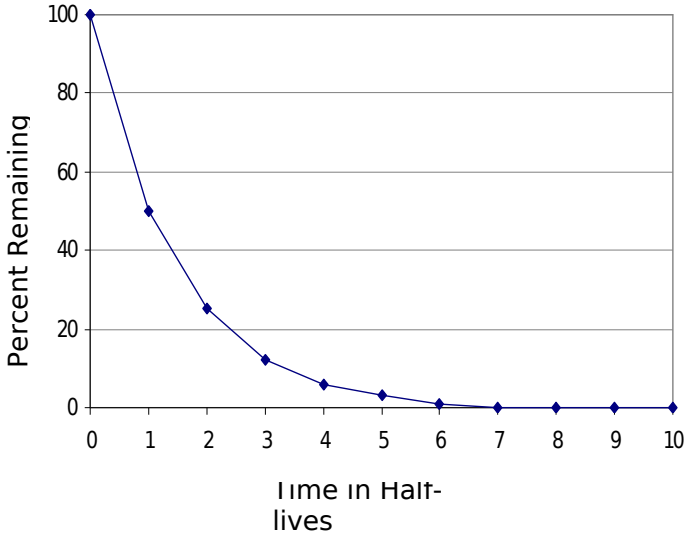
Radioactive Decay

All chemical elements have multiple **isotopes**, some of which are unstable, or radioactive. **Radioactive decay** is the process by which an unstable atomic nucleus becomes more stable by emitting energy in the form of particles or ionizing electromagnetic waves. The nucleus undergoing radioactive decay is called the *parent* nucleus and the nucleus resulting from radioactive decay is called the *daughter* nucleus.

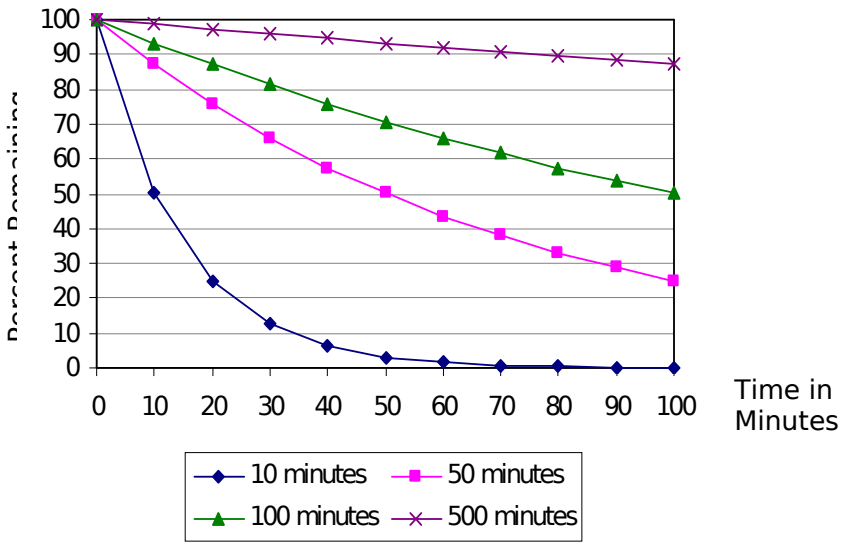
Alpha particles are generally emitted when very heavy **radioisotopes** like uranium-235 and uranium-238 decay. Nuclear reactor fuel fission products generally decay by beta particle emission. Gamma-ray radiation accompanies alpha and beta decays when the resulting daughter nucleus is in an elevated energy state. Since a nucleus wants to be in its ground energy state, an “excited” nucleus will emit one or more gamma-rays to achieve this ground state.

Although the precise time at which the nucleus of a radioactive atom will decay cannot be determined, the average behavior of a very large number of radioactive atoms can be experimentally determined. The average time dependence for the decay of a specific kind of radioactive atom is called the decay constant (λ), which is the probability per unit time that a decay will occur. A unit called **activity**, which is the product of the decay constant and the number of radioactive atoms present (λN), is used to characterize the **radioactivity** of a material. The larger the decay constant or the more radioactive material you have, the higher the activity.

The rate at which radioactive atoms decay is exponential and is characterized by a time called the **half-life** – the average time required for the atoms to decrease to one-half of the initial number present (the half-life of a specific kind of radioactive atom and its decay constant are related by $T_{1/2} = 0.693/\lambda$). After one half-life only 50% of the initial atoms remain, after two half-lives only 25% of the initial atoms remain, etc. After ten half-lives only about 0.1% of the initial atoms remain. This behavior gives rise to the characteristic half-life curve as shown in the graphic below.



The significance of this graphic is that more short-lived atoms undergo radioactive decay than long-lived atoms in real time, resulting in higher activities. Very long-lived isotopes like U-235 and U-238 have relatively low activities because they decay so slowly. As a corollary, relatively short-lived radioisotopes (with half-lives on the order of a day or less) decay away fairly quickly. This becomes more apparent when the percent remaining atoms is plotted in real time, rather than in half-lives, for radioisotopes with half-lives of 10 minutes, 50 minutes, 100 minutes, and 500 minutes as shown in the following graphic.



Whereas **activity** (λN) characterizes the rate of radioactive decay for a radiation source (i.e., disintegrations per unit time), **dose rate** characterizes the rate at which matter is exposed to radiation from a radiation source. Dose rate for a specific radiation type (i.e., alpha, beta, or gamma-ray) depends directly on the radiation source activity, the radiation energy, and the radiation's quality factor, and inversely on the distance of the exposed matter from the source. Therefore, the larger the distance from a radiation source, the smaller the dose rate. Dose rates are generally expressed in millirem per hour or milli-Sieverts per hour.

The **dose** absorbed by biological tissue then depends on the dose rate and the tissue exposure time.